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Three Guises of Generation-Recombination Noise

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Julius Cohen

Center for Radiation Research
National Measurement Laboratory
National Bureau of Standards
Washington, DC 20234

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THREE GUISES OF GENERATION-RECOMBINATION NOISE

Julius Cohen

Radiometric Physics Division
Center for Radiation Research

It is shown that the noise in a zero-biased junction may be just a manifestation of the normally-occurring generation-recombination process, rather than shot noise, as is usually presumed. In addition, an attempt is made to clarify some noise mechanisms in semiconductors by addressing mathematical interpretation and terminology. In particular, for a biased homogeneous material at low frequencies, where the relevant transport mechanism is drift, a shot-like expression of the g-r noise equation is derived. For a zero-biased junction at low frequencies, where the relevant transport mechanism is diffusion, a pure shot-like expression of the g-r noise equation and an equivalent thermal (Nyquist) expression is derived. In both the homogeneous and the junction cases, however, the true noise remains generation-recombination noise, i.e., the origin of the noise is the fluctuations in the rates of generation and recombination of free carriers.

Key words: generation-recombination; junction; noise; semiconductors.

This paper has two objectives: 1) to clarify some noise mechanisms in semiconductors by addressing mathematical interpretation and terminology, and 2) to show how the normally occurring generation-recombination process can alone account for the noise in a zero-bias junction, i.e., without making the usual presumption of another noise mechanism or origin.

That generation-recombination noise is relatively unfamiliar, belies its importance. Indeed, g-r noise is one of the primal noises in semiconductor devices, including photon detectors, and oftentimes it is predominant. G-r noise originates in thermally or optically-stimulated electronic interband transitions or transitions

between impurity levels, traps, or recombination centers and one of the bands, either conduction or valence. Associated with these transitions are fluctuations in the numbers of free carriers and in their lifetimes, thus giving rise to the g-r noise. The mathematical expressions for g-r noise depend on the details of the number of energy levels, the energies corresponding to these levels, the electron population, and the occupancy of states. Formulas for specific models have been derived by van Vliet and co-workers.[1,2,3,4]

An interesting, but sometimes deceptive aspect of g-r noise is that it may appear in several guises, thus obscuring its true identity; hence origin. This paper shows how two basically different guises of g-r noise--a shot form and a thermal (Nyquist) form--may be easily derived from an explicit g-r noise formula, and discusses the significance of the various forms.

As an example, the common case of an extrinsic semiconductor such as germanium or silicon containing both donors and acceptors, one of which is predominant; each of which exceeds in number the number of free carriers[5], will be treated here. The general formula for the extrinsic g-r noise spectrum $S^{(i)}(\omega)$ is given by[1]

$$S^{(i)}(\omega) = 4\,\frac{I^2}{\overline{N}}\alpha\left[\frac{\tau}{1 + (\omega\tau)^2}\right], \tag{1}$$

where

$$S^{(i)}(\omega) = \frac{\overline{i^2}}{\Delta f},$$

$\alpha \equiv \dfrac{\overline{\Delta N^2}}{\overline{N}}$, is a complicated statistical factor,[1,6]

and

$\omega = 2\pi f$, f is the electrical frequency, $\overline{i^2}$ is the mean square noise current, Δf is the noise-equivalent band pass, I is the (steady) direct current, τ is the lifetime of the free carriers, and N is the number of free carriers.

For the particular case being treated here, Eq. (1) reduces to

$$S^{(i)}(\omega) = 4 \frac{I^2}{N} \left[\frac{\tau}{1+(\omega\tau)^2}\right] \quad . \tag{2}$$

At low frequencies, as assumed here for simplification, where $\omega\tau \ll 1$, the term in brackets $\approx \tau$ Hence Eq. (2) may be re-written as

$$S^{(i)}(\omega) = 4\ I^2\tau/N. \tag{3}$$

Because $N = g\tau$, where g is the generation rate, the quantity τ/N in Eq. (3), is just the inverse of the generation rate. (Although the exact noise spectrum formula for other models may not be identical to the above, they are expected generally to be similar.)

The free carriers, on being generated, will undergo some form of transport. Although the transport process itself may contribute a noise in addition to the g-r noise, "transport noise" will be assumed to be negligible. For a bulk material, the zero-bias case is physically uninteresting, as g-r noise apparently is not observed unless a net current is passed, and the preponderant noise mechanism in a passive homogeneous material is thermal agitation noise of the free carriers, i.e., Johnson noise. For the useful case of a bulk material with bias,

the transport mechanism of concern is drift. In pure drift, collisions between the free carriers and the lattice are assumed to be negligible.

For the case of pure drift, Ohm's law is applicable; viz.,

$$J = (N/\upsilon)e\mu E \quad , \tag{4}$$

where J is current density, υ is volume, e is electron charge, μ is mobility, and E is electric field. Expressing N as a function of I and substituting in Eq. (3) gives

$$S^{(i)}(\omega) = 4eI\,(\tau/\tau_d) \quad , \tag{5}$$

where $\tau_d = l^2\,\mu V$ is the carrier drift time across the region l between electrodes, and V is voltage. (This result is consistent with a similar derivation made for a more general case.[7])

Equation (5) resembles that for the classical shot noise of a thermionic diode; viz.,

$$S^{(i)}(\omega) = 2\,e\,I\,\beta \quad . \tag{6}$$

When a thermionic diode is operated in the saturated emission current mode, full (or pure) shot noise is obtained and $\beta=1$. When the diode is operated in the space-charge-limited mode, partial shot noise is obtained and $\beta < 1$. Hence, Eq. (5) is the shot-like form of the g-r noise equation, but it should not be construed as meaning that the g-r noise is shot noise. The origin of g-r noise is the fluctuations in the rates of generation and recombination of the carriers; the origin of true shot noise is the corpuscular nature of electrons, and the noise is associated with emission or conduction.

Equation (5) relates to extrinsic g-r noise in a biased, bulk semiconductor. Now a zero-biased pn junction will be treated: A pure shot-like form of the g-r noise equation will be derived and shown to have a mathematically equivalent thermal (Nyquist) form.

In the bulk regions, which are the regions adjacent to the depletion region (i.e., the junction region proper) the electric field is of negligible strength. Hence, drift is inconsequential and diffusion is the relevant transport mechanism. Of the free carriers in the bulk regions, only minority carriers within a diffusion length L of the junction region are able to contribute to the junction noise, and the appropriate time of transport is the lifetime τ. Those carriers reaching the depletion region boundary are swept across the junction region (by the built-in field), and "instantaneously" collected with virtually no recombination having occurred.

It follows from this model that

$$I \approx Ne/\tau \quad . \tag{7}$$

Substituting the above equation into Eq. (3), one obtains

$$S^{(i)}(\omega) = 4eI \quad , \tag{8}$$

which is the pure shot-like form of the g-r noise equation for a zero-biased junction. Like the previously-treated homogeneous case, the true noise is generation-recombination noise, not shot noise, because the origin of the noise is the fluctuations in the generation and recombination rates of minority carriers, not the discreteness of the electron. Broadly interpreted, however, this noise could be thought of as a shot noise in the sense that the number (concentration)

of carriers fluctuates.

It is axiomatic that the magnitude of the available noise power of a system in thermal equilibrium must be given by Nyquist's theorem--regardless of the particular noise mechanism; i.e.,

$$P = k\ T\ \Delta f \quad . \tag{9}$$

But,

$$P = \overline{i^2}\ R/4 \quad . \tag{10}$$

Thus, from (8), (9), and (10),

$$4\ e\ I\ \Delta f = 4\ k\ T\ \Delta f/R \quad . \tag{11}$$

Equation (11) should not be construed to mean that the shot noise is thermal noise. It merely expresses a mathematical (numerical) equivalence.

The present model ascribes the noise in a zero-biased junction to fluctuations in the number of free minority carriers. In this respect it conforms to established theory.[8] However, where earlier models either presume the existence of shot noise,[9] or otherwise presume that the fluctuations of concern are associated with transport,[8] our model makes no presumption. Instead, it argues that the fluctuations responsible for the junction noise originate in processes known to be occurring; namely, generation and recombination. But the present model does not preclude the possibility of a true shot noise in addition, especially if the junction is forward biased.*

The confusion about noise is abundant. One cause is

*With reverse bias, the depletion region widens, thus increasing the generation within; recombination is negligible by comparison, and the noise is essentially "generation noise," given by Eq. (8) with the factor 4 replaced by 2.

misinterpretation of mathematical formulas;[10] another is ambiguous terminology. At this juncture it is appropriate to discuss briefly the terminology used herein, which conforms with common use.

The physical agents of generation-recombination noise are heat and/or light. These cause fluctuations in the rates of generation and recombination of carriers, which is manifested as noise. Thus, this noise is appropriately termed generation-recombination noise. The carriers' property which fluctuates is their number (concentration).

The physical agent of thermal noise is heat, and the carrier property which fluctuates (owing to thermal agitation) is velocity.[11] Obviously this noise is temperature dependent and its formula is given by the Nyquist formulation. Other common names for thermal noise are Johnson noise, Johnson-Nyquist noise, and Brownian/Brownian movement noise.

The physical basis of pure shot noise is per se the corpuscular nature of the particles and the carrier property which fluctuates is number[12] (concentration). Pure shot noise (all carriers are free) is independent of temperature and dependent only on current.

Basing terminology on the origin of the fluctuations, as is done here, should reduce possible ambiguity.

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arising in the junction ..." [W. Swindell, in Applied Optics and Optical Engineering, Vol. VIII, R. R. Shannon and J. C. Wyant, Eds. (Academic, New York, 1980.] It is not always clear whether the fallacies, real or apparent, arise because of deficiencies in mathematics, analysis, conceptualization, terminology, or exposition, but the result is the same--confusion.

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